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PHYSICS OF THE INNER HELIOSPHERE: MECHANISMS, MODELS
AND OBSERVATIONAL SIGNATURES

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1. INTRODUCTION

The objective of the current grant is the study of selected problems concerned with important physical processes that may occur in the corona and solar wind acceleration region, particularly time-dependent phenomena. We are studying both the physics of the phenomena (e.g. effect of transient momentum deposition on the temporal and spatial variation of the temperature, density and flow speed of the solar wind, formation of shocks, etc.) and the resultant effects on observational signatures, particularly spectroscopic signatures. Phenomena under study include (1) wave motions, particularly Alfvén and fast mode waves, (2) the formation of standing shocks in the inner heliosphere as a result of momentum and/or heat addition to the wind and (3) coronal transient phenomena where momentum and/or heat are deposited in the corona to produce transient plasma heating and/or mass ejections. The study also includes the development of theoretical models for the inner heliosphere, the theoretical investigation of spectroscopic plasma diagnostics for this region, and the analysis of existing Skylab and other relevant data.

During the current reporting period our efforts were directed primarily toward studies on the physics of solar wind flow in the acceleration region (Section 2), a theoretical study on force free fields and coronal heating (Section 3), and on impulsive phenomena in the solar corona (Section 4). These studies, and others that we are planning to undertake, have relevance not only to improving knowledge concerning the physics of the solar wind acceleration region, but also to defining scientific objectives and requirements for instrumentation for the Solar and Heliospheric Observatory, Pinhole Occulter Facility and future Spartan, Sunlab and/or Spacelab flights.

During the current reporting period two papers were presented at a scientific meeting and four were submitted for publication. Several papers submitted for publication earlier have now appeared in the literature. A summary of papers published, submitted and in press as well as presentations at scientific meetings and colloquia are listed in Section 6.

2.0 CORONAL SOURCE REGIONS OF THE SOLAR WIND: MODELS AND MECHANISMS

One of the major objectives of our research program is the development of models for open magnetic regions which generate the solar wind. The goal is to derive models which are constrained to the maximum extent by observational data. These data include existing measurements of spectral line intensities, widths and Doppler shifts near the coronal base (chromospheric-coronal transition region and low corona), measurements of coronal hydrogen Lyman alpha intensities and profiles

between 1.5 and $3.5 R_{\odot}$, broadband measurements of the intensity and polarization of the electron scattered corona between 1.1 and $5 R_{\odot}$, measurements of radio scintillations in the upper corona and at large distances from the sun, *in situ* measurements of plasma parameters in the solar wind at large distances from the sun, and measurements of Lyman alpha radiation scattered by the interplanetary medium.

Most existing models for the solar wind ignore the effects of radiative energy losses and the inward thermal conduction. They also usually assume that all plasma heating occurs below the coronal base. Consequently, models of this type can use only a limited subset of the available empirical information on conditions in the low corona, and therefore extract only a fraction of the information contained in these data. In particular, such models cannot use existing observational data to determine where and how much energy is dissipated in heating the coronal plasma.

In order to avoid these limitations we are using a solar wind model known as a radiative energy balance model. It is based on the stellar wind model developed by Hammer (1982a, 1982b, 1983). This single fluid model employs deposition of mechanical energy beyond the solar surface to generate models with temperature maxima at $r > 1 R_{\odot}$. The current model uses a heating law of the form $dF_m/dr = -F_m/H_m$, where H_m is the characteristic damping length over which most of the heating flux is dissipated. Endler, Hammer and Ulmschneider (1979) have pointed out that many proposed coronal heating mechanisms have heating laws of this form. The model employs collisionless conduction in the outer corona and interplanetary medium and includes the effects of energy losses by radiation and inward thermal conduction. Furthermore, it assumes that the energy transported to the low atmosphere is balanced by the radiative losses there. This yields a relationship between the pressure at the coronal base and the amount of energy deposited there by thermal conduction from the hotter layers of the corona. The end result is a model with only four primary adjustable parameters, the mechanical energy input, its characteristic dissipation length, the nonradial expansion factor, and the Alfvén energy flux. The latter is included since it is a likely candidate for accounting for the extra energy required to generate high speed solar wind (see reviews by Hollweg 1978, 1981; Leer, Holzer and Fla 1982; Pneuman 1986).

The first stage in our program for development of models for open magnetic regions has been completed recently. We have constructed single fluid models for a typical quiet, unstructured region of the corona, an equatorial coronal hole and polar coronal holes at solar maximum and minimum. The radial variation of the measured electron densities in these regions are given in Figure 1. One of the reasons for studying coronal regions with different physical characteristics is that one can obtain more constraints on theoretical models than is possible with only one region (such as

the often used empirical model for the 1973 polar coronal hole derived by Munro and Jackson 1977). Figures 2-4 contain comparisons between calculated and empirical densities, temperatures, and flow velocities for the three coronal holes. Figure 5 compares the temperatures, densities and flow velocities in these regions and a typical quiet region. Based on these models, it appears that most of the energy heating the coronal plasma is dissipated within $2 R_{\odot}$ of the solar surface with a characteristic dissipation length which varies approximately as P^{α} where P is the pressure at the coronal base and $-2 < \alpha \lesssim -1$. The models also suggest that the total nonradiative energy input in magnetically open coronal regions is $5 \pm 1 \times 10^5$ erg cm⁻² s⁻¹.

One of the important characteristics of the model used in the above study is that it links the chromospheric-coronal transition region, low corona and extended corona and solar wind into a single model. This has made it possible to tie together results of EUV observations of the lower atmosphere with observations of the extended corona made with coronagraphic techniques and with measurements of the solar wind far from the sun. For example, one of the results is confirmation of the suggestion by Rottman, Orrall and Klimchuk (1982) that the systematic blue shifts measured in coronal EUV lines in coronal holes are very likely to be caused by the outflow of the solar wind in these features (see Figures 2 and 3). Another interesting result is the finding that the inward conductive fluxes predicted by the model are in excellent agreement with those derived by independent techniques from analyses of measurements of EUV spectral lines formed in the transition region and low corona. The model also predict temperatures in the middle corona ($r = 2$ to $3 R_{\odot}$) in reasonably good agreement with those inferred from measurements of the distribution of ion charge states in the solar wind far from the sun (*e.g.* Figure 2).

One of the important features of the radiative energy balance model is that it appears to offer a basis for the development of a comprehensive model for regions with open magnetic configurations, a model where differences in coronal densities (*e.g.* between coronal holes and quiet regions with open magnetic configurations) and solar wind outflow (low speed and high speed wind) are caused primarily by differences in magnetic geometry. Figure 6 illustrates the results of a simple first order attempt to account for the observed density differences using the current version of the model. The upper and lower set of points are electron densities measured in respectively a typical quiet region and an equatorial coronal hole. The three curves give densities calculated from radiative energy balance models with identical mechanical energy inputs, but different nonradial expansion factors (of 1, 3 and 5). As the nonradial expansion increases in these models, a larger fraction of the available energy is carried outward in the solar wind, reducing the amount transported to the low atmosphere. In a radiative energy balance model the base

pressure is proportional to the magnitude of the inward conductive flux, hence a reduction in this flux leads to a corresponding reduction in density throughout the corona.

The details of the above results are contained in a paper recently submitted to the *Astrophysical Journal* by Withbroe (1987).

We also carried out a study to determine the effects of inhomogeneities in coronal structure on the line profile of the resonantly scattered hydrogen Lyman alpha line. This study was carried out by a R. Esser during her visit to the Center for Astrophysics in collaboration with G. Withbroe. Self consistent two-fluid models with Alfvén waves were developed for representative coronal holes and the surrounding quiet regions. These were then used to calculate theoretical Lyman alpha line profiles for combinations of different types of coronal holes and quiet regions to determine how the intensity and shape of the emergent profile is affected by the line-of-sight integration. The results of the calculations are being analyzed and will be reported at the Midnight Sun Conference on Activity in Cool Star Envelopes in Tromsø, Norway in early July.

3. FORCE-FREE FIELDS AND CORONAL HEATING

We have been doing theoretical work on coronal heating in loop structures. A paper on this subject has been completed and submitted to the journal *Geophysical and Astrophysical Fluid Dynamics* by A. van Ballegooijen. The abstract of the paper is as follows:

"We consider the formation of small-scale magnetic structures in solar coronal loops, with the aim of understanding the possible role of these structures in the process of coronal heating. A simplified model of a coronal loop is discussed. Neglecting loop curvature, we consider an initially uniform magnetic field embedded in a perfectly conducting plasma between two flat parallel plates $z = 0$ and $z = L$, which represent the photosphere at the ends of the loop. Slow, random motions at these boundary plates produce twists and braids in the magnetic field. We discuss the properties of such braided fields assuming the field evolves through a series of force free equilibria.

Using a Lagrangian description of the field, the equilibrium problem is formulated as a boundary-value problem for the functions $X(x_0, y_0, z, t)$ and $Y(x_0, y_0, z, t)$, which describe the shape of the field lines characterized by the initial coordinates x_0 and y_0 . It is shown that $X(x_0, y_0, z, t)$ and $Y(x_0, y_0, z, t)$ are continuous functions of x_0 and y_0 at time $t = T$ provided X and Y are continuous at $z = 0$ and $z = L$ for all intermediate times $0 < t < T$. This implies that spatially continuous

velocity fields at the boundary plates do not produce tangential discontinuities in the magnetic structure as first suggest by Parker (1972). It also implies that ideal-MHD instabilities, if they occur in this model, do not lead to tangential discontinuities. We contrast our results with those obtained for more complicated field topologies containing multiple flux systems. Instead of the catastrophic process of current-sheet formation envisioned by Parker, we propose a more gradual process in which small-scale magnetic structures are produced by the random intermixing of fluid particles in the photosphere."

4. IMPULSIVE PHENOMENA IN THE SOLAR CORONA

One of the objectives of our research program is the development of techniques for placing empirical constraints on the mechanisms for coronal heating. We have undertaken several studies of VLA radio observations in order to exploit existing data for this purpose and to gain insights as to what types of observations should be acquired in the future with ground-based instruments, SMM, and future missions such as SOHO.

We have also been studying coronal bright points with a variety of recently acquired observations. Simultaneous observations of bright points at radio and optical wavelengths were made in September 1985 with good temporal (1-5 min) and spatial (few arc sec) resolutions. The observations were carried out at the VLA (S. Habbal), National Solar Observatory (K. Harvey), Big Bear (F. Tang), Marshall Space Flight Center (M. Haygard), Ottawa River Solar Observatory (V. Gaizauskas), Owens Valley Radio Interferometer (G. Hurford) and SMM. (The acquisition of the VLA data and the computer time needed to reduce the data have been provided by internal funds.) These data are the first measurements to show the direct correspondence between coronal bright points and He $\lambda 10830$ dark points. The observed radio emission, which originated at heights typical of the low chromospheric-coronal transition region (*cf.* Habbal *et al.* 1986), exhibits substantial spatial and temporal variations in bright points, very similar to the variability found at EUV and optical wavelengths. A paper describing these results was completed and published in the Proceedings of the Workshops on Coronal and Prominence Plasmas (Habbal and Harvey 1986). A more detailed study of the radio and He $\lambda 10830$ data was also completed and submitted for publication in the *Astrophysical Journal* by the same authors. The abstract of the latter paper is given below.

"We present the results of the first simultaneous observations of the quiet Sun made at the 20 cm radio wavelength and in the He I $\lambda 10830$ Å line. Simultaneous magnetic field measurements were also obtained with lower time resolution during the five consecutive hours of observations. In the 512"x512" common observing field of view we find that 60% of the 20 cm radio emission features, which originate from

the low corona-transition region, have strong He I $\lambda 10830$ 'dark points' associated with them. In the other 20 cm sources, the underlying He I absorption is rather weak except for very localized (1-5") enhancements comparable to the strong dark points. The radio emission at 20 cm suggests that the quiet Sun corona is threaded by magnetic field lines interconnecting He I dark points and magnetic network elements. These 20 cm radio sources, ranging in spatial extent from 20" to 50", are reminiscent of coronal bright points detected originally at X-ray and EUV wavelengths.

The intensity of the emission at 20 cm and absorption in He I $\lambda 10830$ in the observed sources changes significantly over a time scale often as short as three minutes, the shortest time scale available in the data. This dynamic behavior is also accompanied by changes in the spatial extent of the sources observed at 20 cm, and is more often associated with the cancellation than the emergence of magnetic flux. The nature of the correlation found between changes in He I $\lambda 10830$ dark points and the 20 cm radio sources, as well as with the underlying magnetic field, offers new observational constraints and poses new questions regarding the dynamical relationship between the photospheric magnetic field, the chromosphere and low corona-transition region in the quiet Sun."

5. FUTURE WORK

We plan to continue our work on: the theoretical study of time-dependent and steady-state phenomena in the solar wind acceleration region; the development of models for this critical region of the heliosphere; the theoretical development of spectroscopic plasma diagnostics for the inner corona and solar wind acceleration region; coronal heating mechanisms; and empirical studies of impulsive heating using Skylab and radio data. We also plan to continue our collaboration with E. Leer and R. Esser (Norway) on the study of Alfvén wave driven solar winds.

6. PAPERS PRESENTED, SUBMITTED FOR PUBLICATION OR IN PRESS

1981

Withbroe, G. L. 1981, "Spectroscopic Probing of the Solar Wind Acceleration Region", colloquium presented at University of New Hampshire, December.

1982

Habbal, S. R. and Tsinganos, K. 1982, "Stellar Winds with Multiple Critical Points and Shock Transitions", presented at 160th meeting of American Astronomical Society, Troy, June, *Bull. Amer. Astron. Soc.*, **14**, 608.

Owocki, S. 1982, "Interpreting the Solar Wind Ionization State", talk presented at University of Maryland Space Physics Group, Goddard Space Flight Center High Energy Astrophysics Group, Massachusetts Institute of Technology Space Physics Group, and Los Alamos National Laboratory Solar Wind Group, October.

Withbroe, G. L. and Kohl, J. L. 1982, "Spectroscopic Diagnostics for the Solar Wind Acceleration Region", invited paper presented at Theory Conference in Solar-Terrestrial Physics, Boston College, August.

Withbroe, G. L., Kohl, J. L., Weiser, H. and Munro, R. H. 1982, "Probing the Solar Wind Acceleration Region Using Spectroscopic Techniques", invited paper, *Space Sci. Rev.*, **33**, 17.

1983

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a New Class of Shock Transitions in Solar and Stellar Winds", paper presented at Solar Wind V conference, Woodstock, VT, November 1982. In *Solar Wind V*, NASA Conference Publication 2280, ed. M. Neugebauer, p213.

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- Withbroe, G. L. 1983, "The Role of Spicules in Heating the Solar Atmosphere, Implications of EUV Observations", *Astrophys. J.*, **267**, 825.
- Withbroe, G. L. 1983, "Probing the Solar Wind Acceleration Region", colloquium presented at Naval Research Laboratory, Washington, D. C., February.
- Withbroe, G. L. 1983, "Evidence for Temporal Variations in Polar Plumes", *Solar Phys.*, **89**, 77.
- Withbroe, G. L. 1983, "Solar Wind and Coronal Structure", review paper presented at National Academy of Sciences--European Science Foundation Workshop on Solar and Space Physics, Hilton Head, S. C. In *ESA Journal*, **7**, 341.

1984

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Withbroe, G. L., "Corona and Solar Wind", invited paper presented at Workshop on Solar High-Resolution Astrophysics using the Pinhole/Occulter Facility, May 8-10, Huntsville, AL.

Withbroe, G. L., "Impulsive Heating in the Solar Atmosphere", colloquium presented at the University of New Hampshire, Durham, May 23.

Withbroe, G. L., "Origins of the Solar Wind in the Corona", invited paper presented at 19th ESLAB Symposium on The Sun and the Heliosphere in Three Dimensions, Les Diablerets, Switzerland, 4-6 June. Published in conference proceedings in 1986 (R. G. Marsden, ed.), (Reidel, Dordrecht), p. 19.

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Withbroe, G. L., "Corona and Solar Wind", in E. Tandberg-Hanssen, R. M. Wilson, H. W. Hudson (eds), *Solar Flares and Coronal Physics using P/O as a Research Tool*, NASA Conference Publication 2421, p. 221.

1987

Habbal, S. R., Gonzalez, R. and Harvey, K. L. "Simultaneous Observations of the Quiet Sun at 90 and 20 cm Radio and He 10830 Wavelengths", presented at AAS meeting 169, Pasadena, CA.

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van Ballegooijen, A. A. "Force Free Fields and Coronal Heating. I. The Formation of Current Sheets", submitted to *Geophys. Astrophys. Fluid Dyn.*

Withbroe, G. L., "The Temperature Structure, Mass and Energy Flow in the Corona and Inner Solar Wind", submitted to *Astrophys. J.*

Figure 1. Radial variation of electron density in four regions. The curves give densities determined primarily from broad-band measurements of electron-scattered white light radiation, the points give densities determined from measurements of the intensities of EUV spectral lines. The triangular point is from a quiet region, the open square from a polar coronal hole at solar maximum, the open circle from an equatorial coronal hole and the filled circles from a polar coronal hole at solar minimum. Data sources are Saito (1970), Allen (1973), Munro and Jackson (1977), Saito *et al.* (1977), Lallement *et al.* (1986), Withbroe *et al.* (1985, 1986).

Figure 2. Comparison of empirical densities, temperatures and flow velocities (points) with those calculated with a single fluid radiative energy balance solar wind model (curves). The solid curve is for a thermally driven wind; the dashed curves include deposition of differing amounts of Alfvén wave flux. The empirical densities are from an equatorial coronal hole (see Figure 1); the empirical temperatures marked by open points are based on measurements of charge states in the solar wind far from the sun; the empirical temperatures marked by filled points are based on EUV data; the empirical velocities near $r = 1.1 R_{\odot}$ are based on measurements of spectral line Doppler shifts; the empirical velocities at $215 R_{\odot}$ are based on in situ data. Data sources: Cushman and Rense (1976), Feldman *et al.* (1977), Rottmann *et al.* (1981, 1982), Schwenn (1983), Ipavich *et al.* (1983, 1986), Galvin *et al.* (1984), Marsh and Richter (1984), Withbroe (1987).

Figure 3. Same as Figure 2, but for a polar coronal hole at solar minimum. However, the flow velocities near 7 and $215 R_{\odot}$ are from radio scintillation data. Data sources: Mariska (1977, 1978), Tyler *et al.* (1981), Orrall *et al.* (1983), Scott *et al.* (1983), Coles and Rickett (1986).

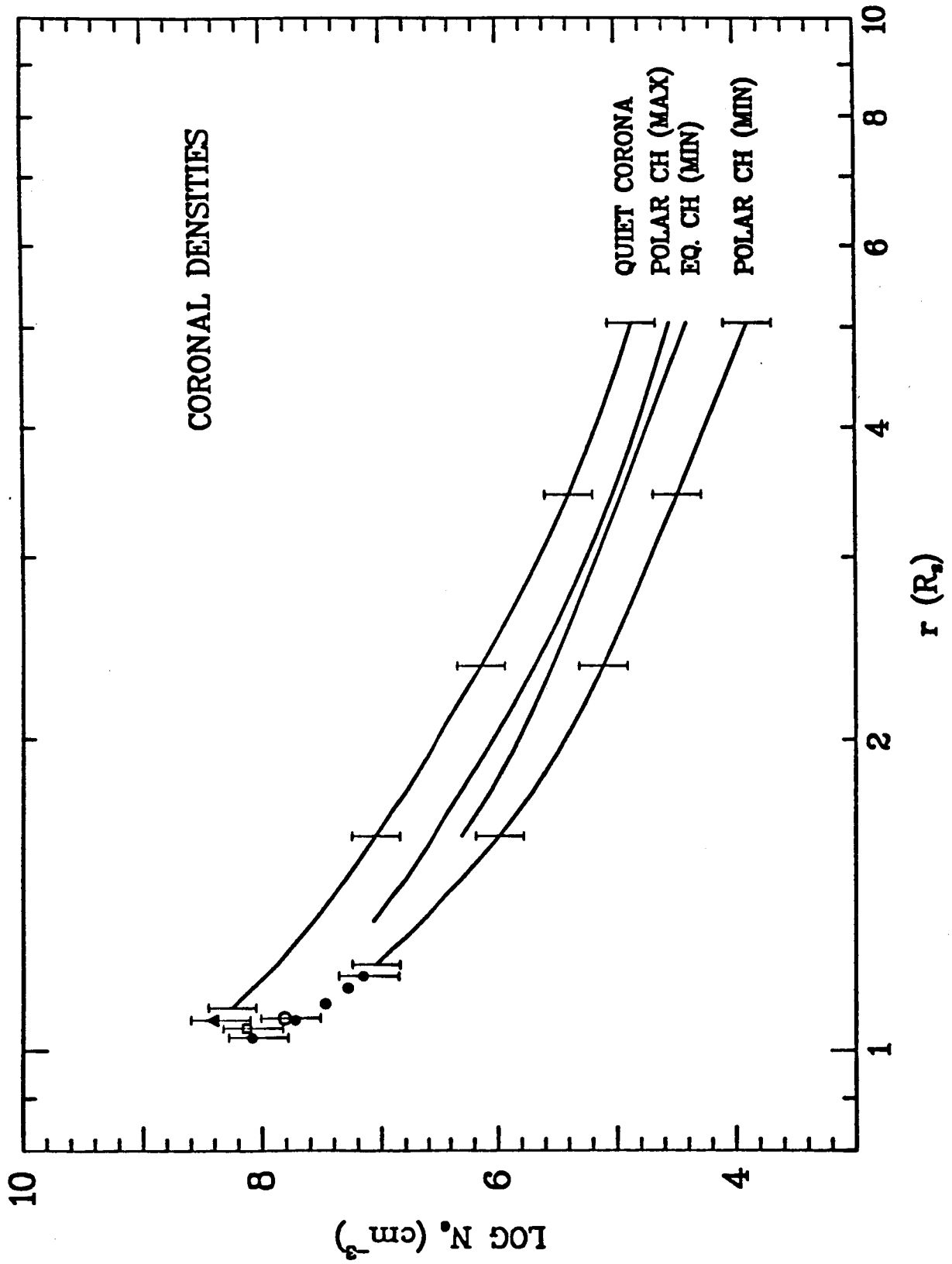
Figure 4. Same as Figure 2. However, the empirical flow velocity at $4 R_{\odot}$ is based on Lyman alpha Doppler-dimming data, the empirical velocity at $215 R_{\odot}$ is based on radio scintillation data. The temperatures near $1.5 R_{\odot}$ are based on coronal Lyman alpha spectral line profiles. Data sources: Rickett and Coles (1983), Withbroe *et al.* (1985, 1986), Coles and Rickett (1986).

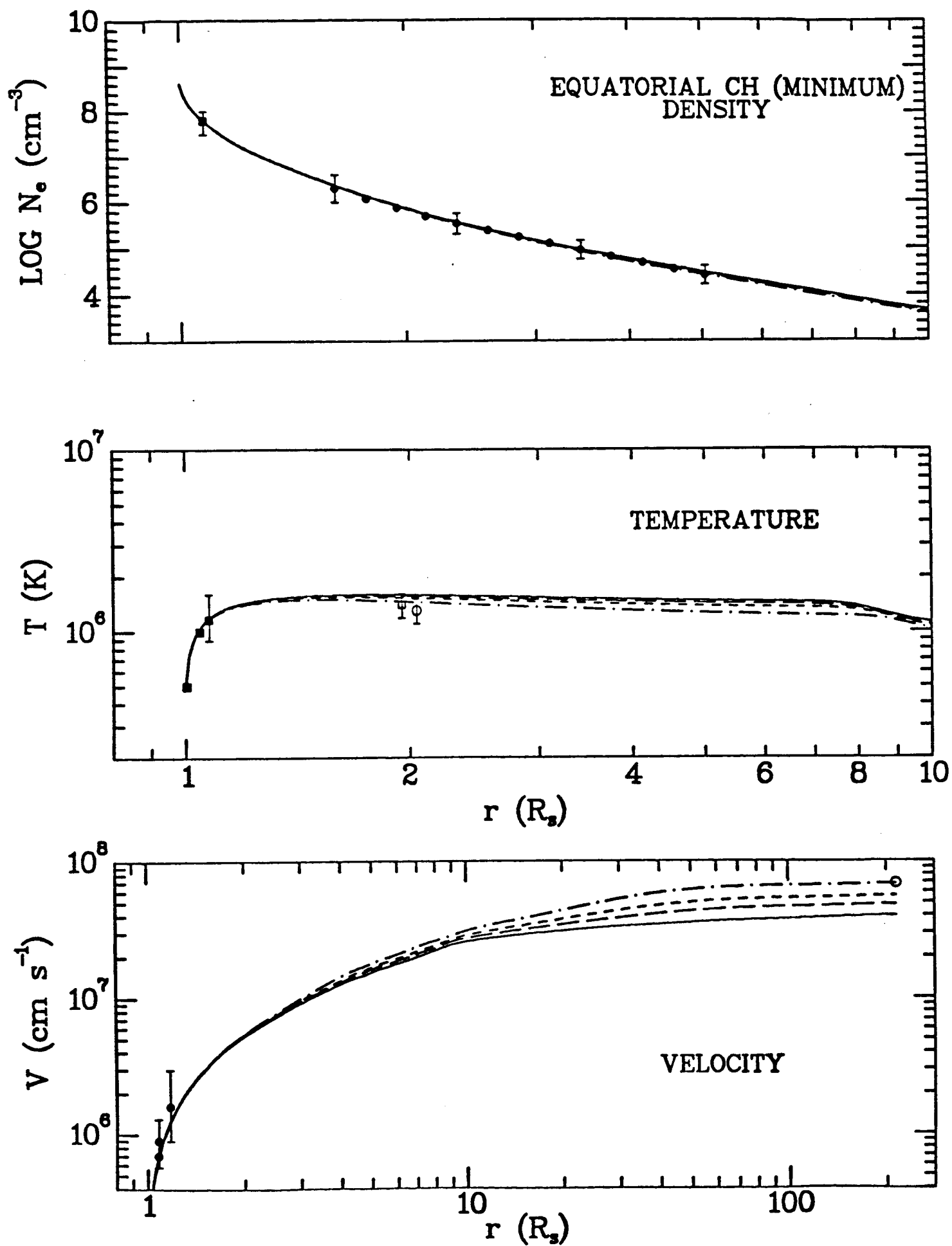
Figure 5. Comparison of densities, temperatures and flow velocities for models of quiet region (solid line), polar coronal hole at solar maximum (long dash line), equatorial coronal hole (short dash line), and polar coronal hole at solar minimum (dot-dash line).

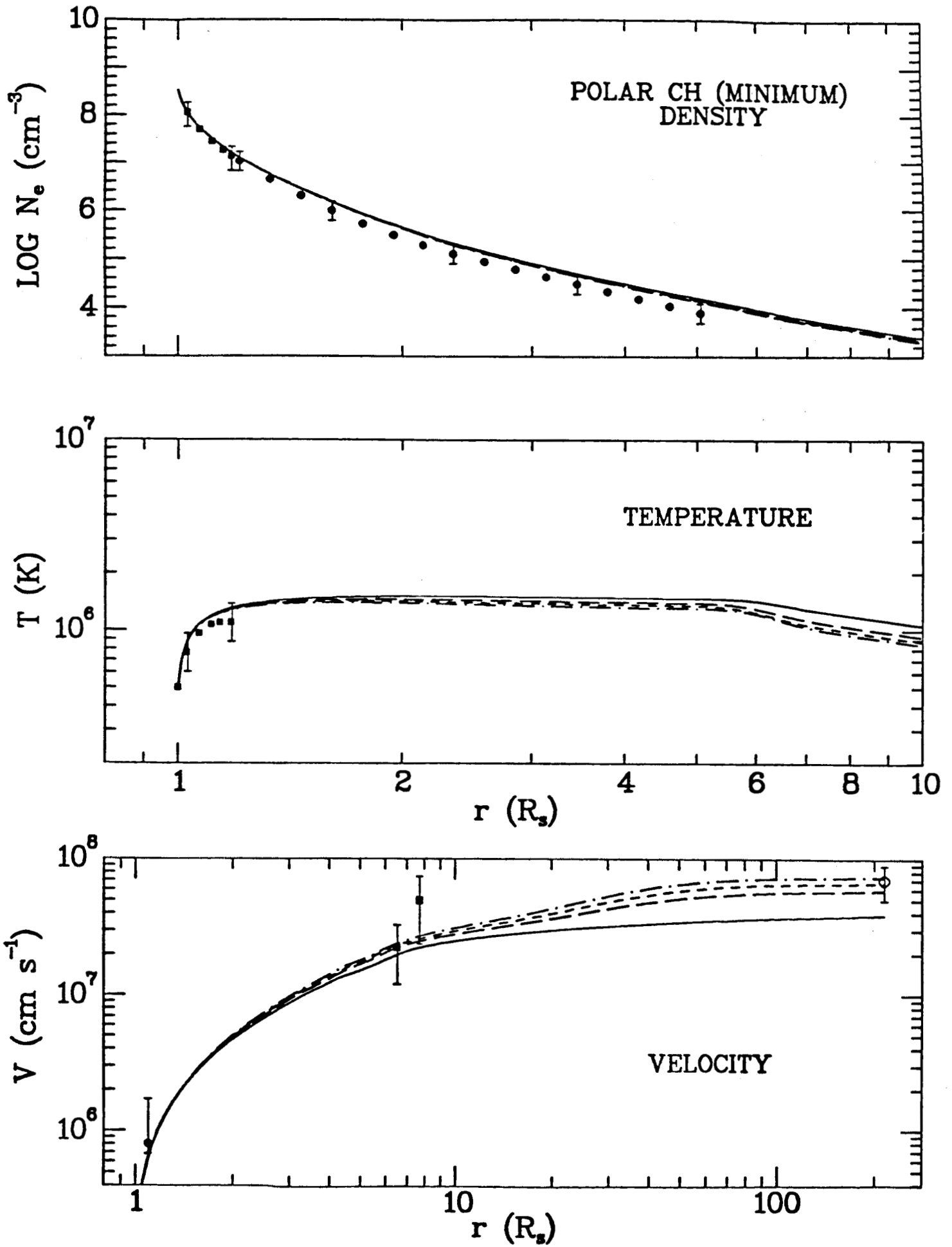
Figure 6. Coronal densities calculated for models with identical mechanical energy inputs, but different nonradial areal expansion factors ($=1$ for the solid curve, 3 for the long dash curve and 5 for the short dash curve--the latter a typical value for equatorial coronal holes). The upper set of points are empirical densities for a quiet region, the lower set of points are empirical densities for an equatorial coronal hole (see Figure 1).

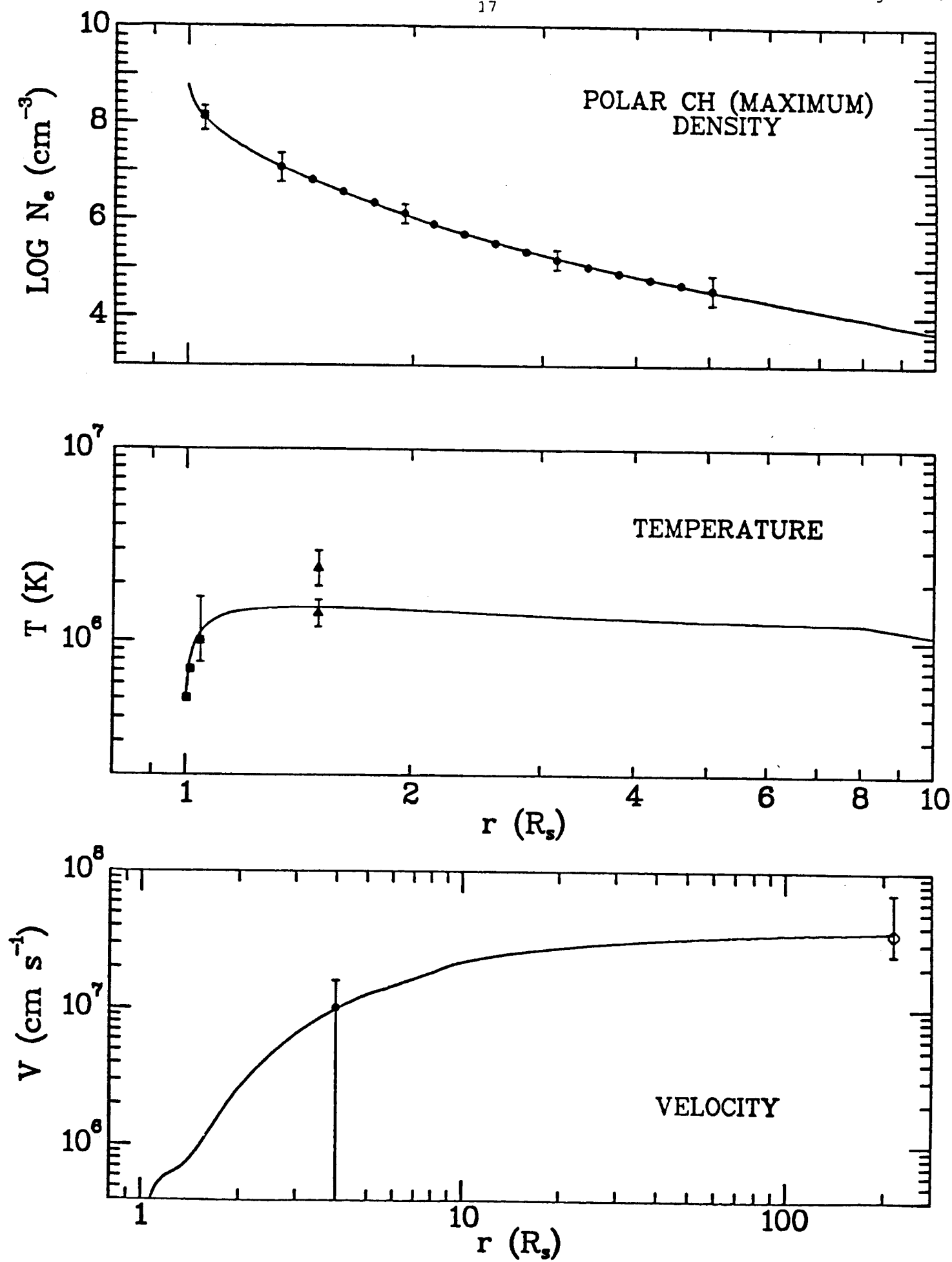
Figure 1.

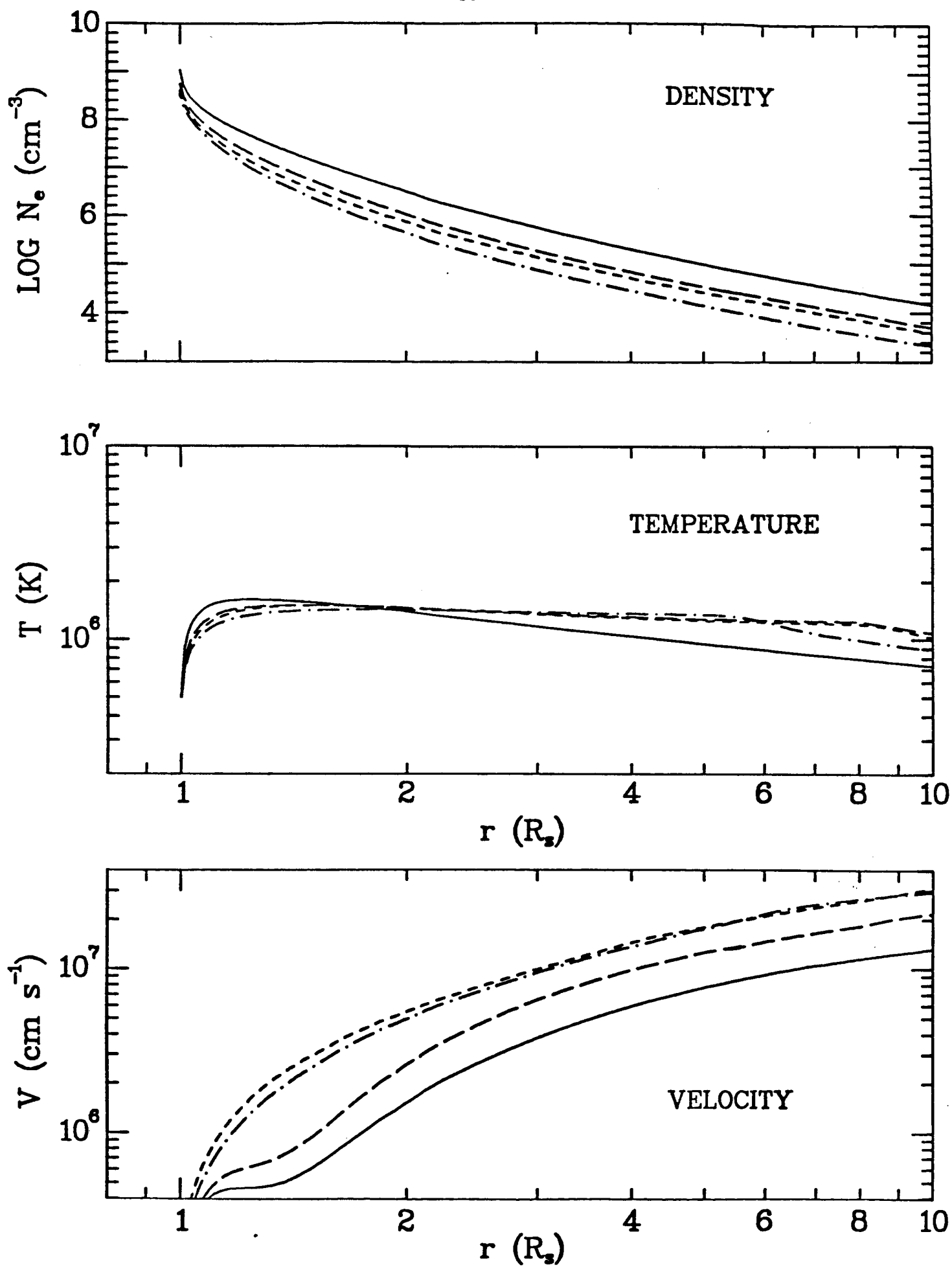
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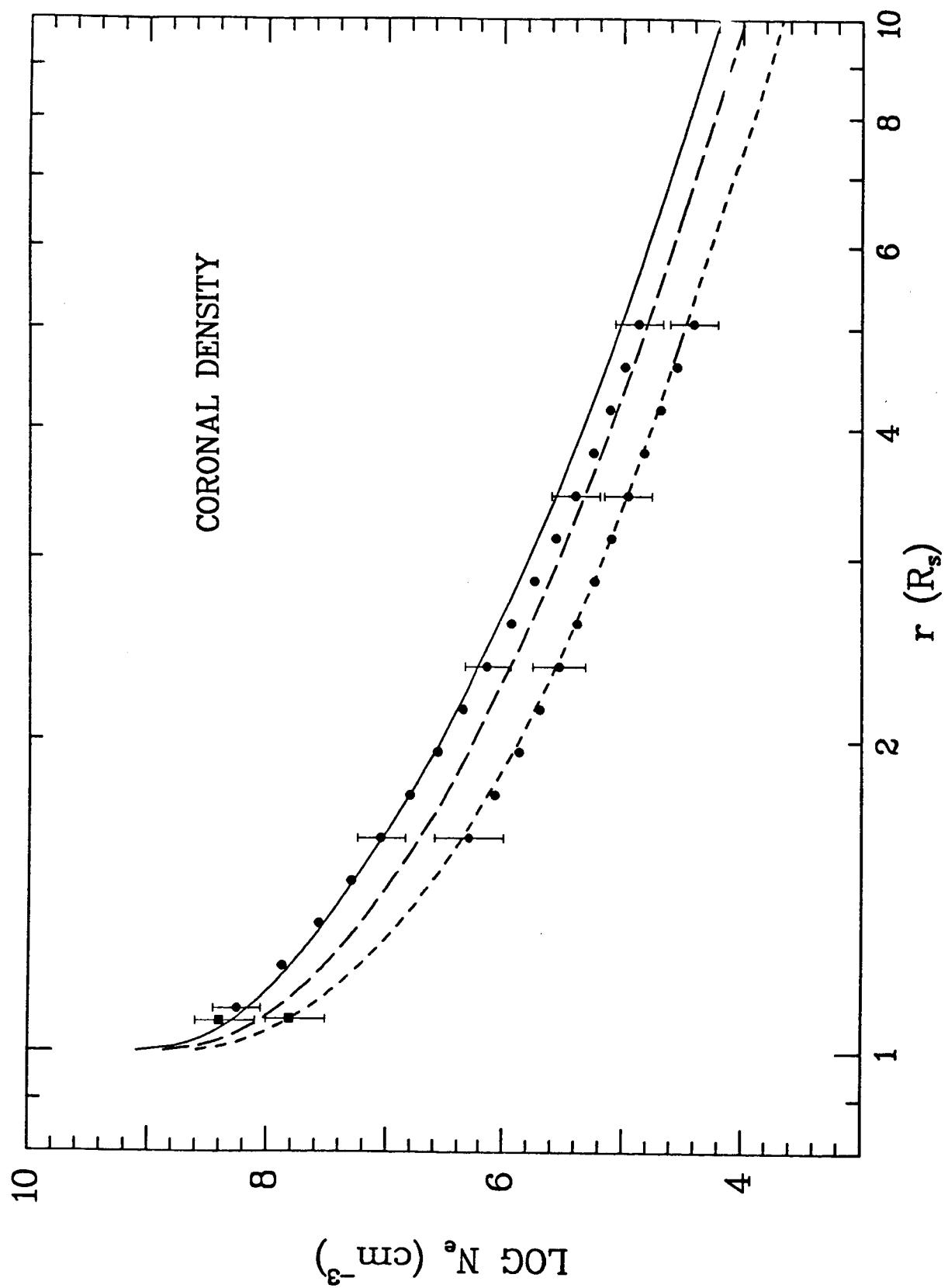












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